

THE SHIELDING DESIGN OF BERLinPro*

K. Ott[†], M. Helmecke, Helmholtz-Zentrum Berlin, BESSYII, Berlin, Germany

Abstract

The Helmholtz-Zentrum Berlin started in January 2011 the design and construction of the Berlin Energy Recovery Linac Project BERLinPro as a demonstrator of ERL science and technology. BERLinPro consists of a SRF photo injector, a merger, superconducting booster and linac modules, the ring and a beamdump [1]. The energy is 50 MeV, the maximum current of is 100 mA (cw), acceleration to higher energies is an option for the future. The low energy parts of the machine are operated at about 10 MeV. Due to the potential radiation hazard posed by the tremendous beampower the facility will be placed subterraneously. The shielding concept is presented here. We used the Monte Carlo code FLUKA to calculate the details of the shielding, activations, energy doses for radiation damage and energy spectra for realistic scenarios. Due to computing time reasons we used FLUKA calculations in the 50 MeV to 1 GeV range to derive analytical formulas for the vertical shielding. Extrapolation of existing formulas valid in the GeV range (or below 100 MeV) are not applicable because of the rapidly increasing cross section of photo pion production between 100 and 200 MeV.

MACHINE DESCRIPTION

The intended cw operation with a current of 100 mA requires an electron source with 77 pC/bunch charge at 1.3 GHz repetition rate. This will be realized by a photo driven SRF gun. The injection linac boosts the energy from the gun to 5 - 10 MeV which corresponds to 0.5 - 1 MW beam power at 100 mA.

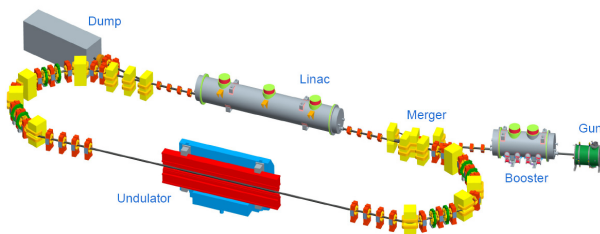


Figure 1: BERLinPro overview

The electrons are further accelerated to 50 MeV in the linac module after one turn the electrons are decelerated in the linac module to the injection energy due to a phase shift of $\lambda/2$. The energy from the decelerated electrons is

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[†] klaus.ott@helmholtz-berlin.de

stored in the linac module and is used to accelerate subsequent electrons (ERL principle). The decelerated electrons are deflected and absorbed in the beam dump.

Table 1: Recirculator Parameters

Energy :	50 MeV (100 MeV)
Current :	100 mA
Nominal charge / bunch :	77 pC / bunch
Circumference :	53.4 m
Straight sections :	2 x 9.8 m, 2 x 1 m
Normalized emittance :	< 1 mm mrad
Number of dipoles :	8
Dipole field :	0.21 T

The electron losses in the recirculator ring are limited by the rf power of the linac module. The rf power of 30 kW corresponds to the small percentual value of 0.6 %. Higher losses e.g. due to a mis-steered beam causes a beam break up.

CALCULATIONS

We started with the FLUKA [2] simulation of the recirculator using one point source. The electrons of 50 MeV hit the vacuum tube of stainless steel with an angle of 1 mrad. The gamma radiation reaches dose rates up to 1.9E5 Sv/h shown in fig. 2 which is about three orders of magnitude higher than the neutron dose rates in fig. 3 in forward direction.

In the lateral direction the values of gamma and neutron radiation are approximately the same. This makes it favorable to place BERLinPro subterraneously, because one has to shield only the lateral radiation vertically. The neutron dose rates show the isotropic radiation distribution which is typical for giant resonance neutrons. But there is also a contribution in forward direction caused by high energy neutrons ($E > 20$ MeV). The source of these neutrons are quasi deuteron fission processes whose threshold energy is about 30 MeV. A second source of high energy neutrons are photo-pion processes with a threshold energy of about 150 MeV. The cross sections of the high energy neutron production is about one order of magnitude lower than that of giant resonance neutrons. But the high energy neutrons are far less attenuated in shielding materials, so the tenth value layers for high energy neutrons are about twice as thick as for giant resonance neutrons. Above the shielding the annual dose limit of 1 mSv/a has to be hold, so from the dose rate values in lateral direction it is clear that several meters of shielding are necessary and the dose rate outside the

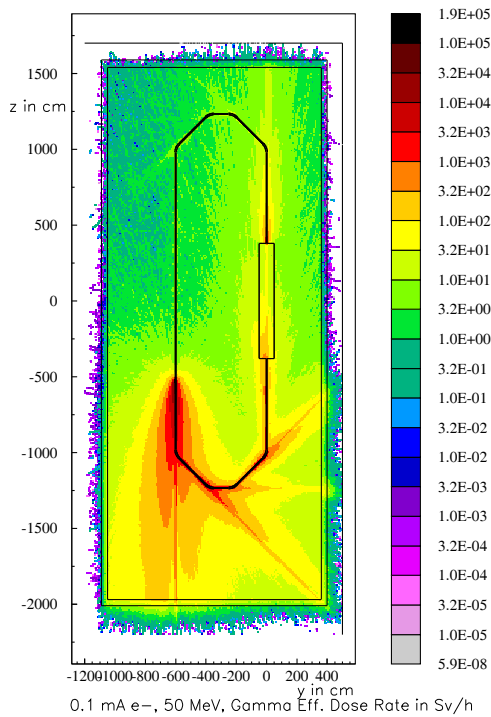


Figure 2: Gamma dose rate from one point source

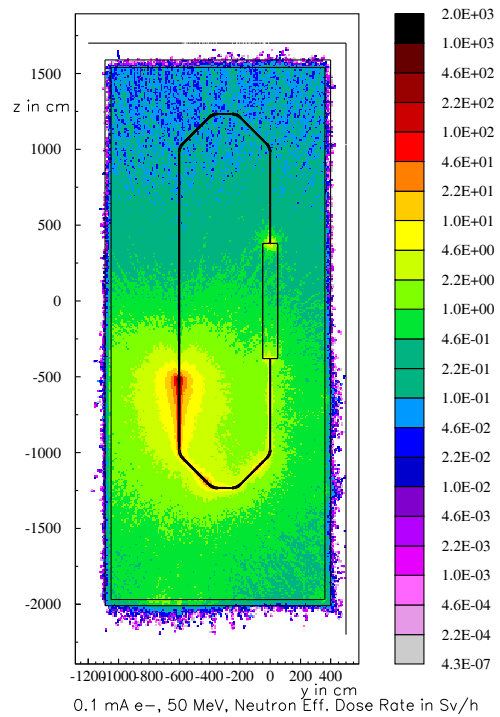


Figure 3: Neutron dose rate from one point source

shielding will be dominated by high energy neutrons. Giant resonance neutrons have a maximum in the spectrum at about 1 MeV, the high energy neutrons shoulder exists only rudimentary because of the 50 MeV electron energy. A second maximum at 25 meV is from neutrons that are thermalized in the concrete enclosure. For shielding calculations the usage of Monte-Carlo codes is problematic in this case due to the required thick shielding and the resulting computation times. Analytic shielding formulas exist for electron accelerators in the GeV range e.g. [3],[4],[5]. In the low energy range (< 100 MeV) [6] no formulas are given for high energy neutrons. Extrapolations of the GeV formulas down to low energy are erroneous (especially for neutrons) because of the rapidly rising cross sections for photo-pion production of high energy neutrons between 150 and 400 MeV. We therefore derived analytical formulas from FLUKA calculations between 50 MeV and 1 GeV with different target and shielding materials in transversal direction [7] starting from [3] and [4] for γ radiation and [5] for neutron radiation. The γ dose in Sv/primary electron is then

$$H = 3.45 \cdot 10^{-17} \cdot t^{2.436} \cdot \ln Z \cdot msc \cdot E \cdot \exp(-(\rho \cdot x - 75 \text{g/cm}^2)/\lambda/r^2) \quad (1)$$

Z is the atomic number of the target material, t is the target transmission in radiation lengths, $msc = 0.01828$ (material scaling factor), E is the energy in GeV, ρ is the density of the shielding material in g/cm^3 , λ is the attenuation

length in g/cm^2 , x is the thickness of the shielding in cm, r is the distance in m. For the giant resonance neutrons we found as dose in pSv/primary electron:

$$H_{GN} = \eta \cdot 0.24 \cdot A^{2/3} \cdot E \cdot (0.33 + 0.67 \sin \theta) \cdot \exp(-\rho \cdot x / \lambda_{GN}) / r^2 \quad (2)$$

η is a target efficiency factor [6],[3] it is 1 for 10 radiation lengths (rl) and 0.3 for two rl, A is the atomic mass number, θ the angle of observation in degrees, the other symbols have the same meaning and units as before. $\lambda_{GN} = 30.25 \text{g/cm}^2$ for concrete and 23.9g/cm^2 for sand. For the high energy neutrons we have as dose in pSv/primary electron:

$$H_{HEN} = K(E) \cdot 23 \cdot A^{-2/3} \cdot E^{1.1} / r^2 \cdot (0.07 + 0.93 \cdot e^{-\theta/31^\circ}) \cdot e^{-\rho \cdot x / \lambda_{HEN}} \quad (3)$$

λ_{HEN} depends also from θ and is 94.4g/cm^2 both for concrete and sand at 90° . $K(E)$ is a correction factor for high energy neutrons and is

$$K(E) = 1 - \frac{1}{\exp(E \cdot 10.52 - 3.59) + 1} \quad (4)$$

ACTIVATIONS

At electron accelerators most nuclear reactions occur by (γ, n) processes caused by photons, that are produced in electro-magnetic cascades. Other reactions (in much

smaller amount) are caused by secondary neutrons (also with thermal energies) and by protons. Because of the pair creation the photon spectra decrease rapidly at energies > 1 MeV. Threshold energies for (γ,n) reactions are about 10 MeV for the materials usually used for vacuum components. We use FLUKA to calculate the production rates \dot{N} of the radio nuclei. We get the activation using \dot{N} and irradiation/decline cycles during one year. After ν irradiation/ decline cycles the activity is:

$$A_{\nu} = \dot{N}^{+} \cdot [1 - e^{-\lambda \cdot t_I}] \cdot e^{-\lambda \cdot t_D} \cdot \frac{1 - e^{-\nu \cdot \lambda (t_I + t_D)}}{1 - e^{-\lambda (t_I + t_D)}} \quad (5)$$

$\lambda = \ln 2/T_{1/2}$. For BERLinPro we used $\nu=365$, irradiation time $t_I = 8$ h, decline time $t_D = 16$ h for the calculation of the activation after one year and $\nu=1$ and $t_I = 8$ h, $t_D = 0$ after one irradiation period.

Activation of Vacuum Components

We compared the activity of three materials used for vacuum components: Al, stainless steel and Cu. For the calculations we used an aluminum alloy with 97.65 % Al.

Table 2: Activation Vacuum Components

Target	Nuclide 1	Nuclide 2	Nuclide 3	Nuclide 4
Al	²² Na	²⁴ Na	-	-
$T_{1/2}$	2.603 a	14.7 h	-	-
Steel	⁵² Mn	⁴⁸ V	⁵⁶ Co	⁵⁵ Fe
$T_{1/2}$	5.6 d	15.97 d	77.26 d	2.73 a
Cu	⁶⁴ Cu	⁵⁸ Co	⁶⁰ Co	
$T_{1/2}$	12.7 h	70.86 d	5.272 a	

The γ dose rate range in 1 m distance is several 100 μ Sv/h for Al, few mSv/h for stainless steel and up to Sv/h for Cu. Considerable is also the β surface dose rate for ⁵⁵Fe which is up to several 100 Sv/h. At that point we remind, that the calculations have been conducted for a point source with 5E-4 electron losses/turn which is very conservative.

After one year of operation the activation of the Al alloy are one order of magnitude lower than stainless steel, or a factor 20 lower than copper. The short living nuclei produced in copper (after 1 irradiation period) has very high activities, so that the access to the bunker has to be restricted. Altogether the usage of Al for the vacuum system is most favorable. At the low energy parts of the accelerator (injector, beam dump) the electron energy is below the threshold for the subsequent (γ,n) activation reactions, so also steel or copper can be used for vacuum components.

Activation of Air

After 8 hours of irradiation the following radio nuclei are produced in the air of the bunker C_A is the activation concentration in Bq/m³ tab. 3. The values requires to measure the activated air given in the environment.

Table 3: Activation of Air

Target	Nuclide 1	Nuclide 2	Nuclide 3	Nuclide 4
Air	¹¹ C	¹³ N	¹⁵ O	⁴¹ Ar
$T_{1/2}$	20.38 m	9.96 m	2.03 m	1.83 h
C_A	1.72E+06	1.67E+06	1.92E+06	3.08E+05

RESULTS

We calculated the dose rate inside the BERLinPro ceiling consisting of 20 cm concrete and sand using the derived analytical formulas as shown fig. 4. The γ dose rate (not shown here) is similar to the giant resonance neutron dose rate. A shielding of 20 cm concrete and 3 m sand is sufficient to hold the annual dose limit of 1 mSv/a above the ceiling. At these thickness the dose is determined by fast energy neutrons.

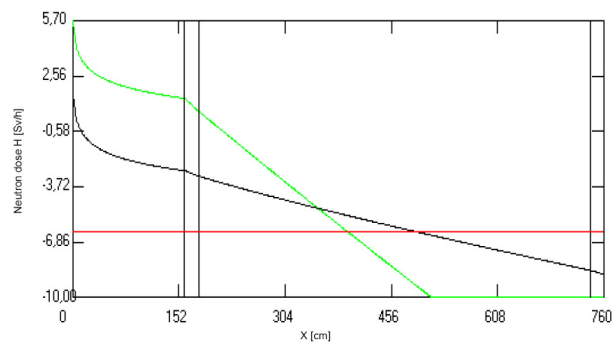


Figure 4: 1g of Neutron Dose rate in Sv/h, green: giant resonance neutrons, black high energy neutrons, red: 0.5 μ Sv/h (1 mSv/a)

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